

**DESIGN AND CONSTRUCTION OF SMART MATERIALS BASED ON  
PIEZORESISTIVE SENSORS AND MULTILAYER ACTUATORS**

**FINAL PROGRESS REPORT**

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PTCR (positive temperature coefficient of resistance) barium titanate was the active material for a ceramic sensor which employed piezoresistivity to detect changes in applied stress. High purity, chemically prepared barium titanate was donor-doped at an optimum level of 0.30 at% lanthanum to provide semiconductivity. A transition metal counterdopant was added at a level of less than 0.10 at% in some cases, to enhance the PTCR effect. The donor dopant and counterdopant were added to the powder through a special precipitation technique. Tape-cast sheets of undoped and PTCR BaTiO<sub>3</sub> were laminated to produce a three-layer "trilaminate" - a sintered structure which has two semiconducting PTCR layers separated by an insulating layer. The trilaminate was exposed to mechanical stress in a four-point bend configuration (placing one semiconducting layer completely in tension, the other in compression), and the resistivities for both stress states were measured concurrently as functions of applied stress and temperature.

Piezoresistivity was found to be extremely sensitive to temperature, reaching a peak just above the Curie temperature,  $T_C$ . The piezoresistive effect, which was positive in compression and negative under tensile stress, was dependent on the presence of a well-formed grain boundary potential barrier, but the species of counterdopant had little impact. Formation of (Ba,Sr)TiO<sub>3</sub> solid solutions shifted the peak to lower temperatures (corresponding to the  $T_C$  shift), and reduced its magnitude. Broadening of the piezoresistivity peak is observed as the thickness of the semiconducting layers of the trilaminate decreases.

The results were in semi-quantitative agreement with a potential barrier model for PTCR BaTiO<sub>3</sub>. This model is based on the Heywang model of the grain boundary as a back-to-back Schottky barrier, in combination with Devonshire's thermodynamic phenomenology which describes polarization in terms of electric field, mechanical stress, and temperature. Original modifications to this combined model account for the non-linear electric field dependence of polarization in the vicinity of the grain boundary, and the circular dependence of field, polarization, and potential barrier height.

A smart material package consisting of piezoresistive sensors and a piezoelectric actuator has been proposed. The proposed device has the advantage of requiring only a simple resistor network as a control circuit and a DC voltage source. The piezoresistive sensor will allow a mechanical stress to control the response of the actuator by controlling the amount of power let through.

The responses of such a smart material package were analyzed using finite element methods. Results of simplified analyses were compared to closed form solutions in order to determine the degree of accuracy of the more complex models. Static and dynamic responses of the package were simulated over a wide range of pressures. Results of the finite element analysis of the piezoelectric effect matched the results of the closed form solutions within 1 %. The enhanced compliant nature of the device was demonstrated under both static and dynamic pressures. The developed algorithms can be used for analysis of packages having different geometries or containing different materials.

The piezoresistive sensor proposed for use in this smart package is an 0-3 ceramic/polymer composite. Such a material has been shown to have order of magnitude decreases in resistivity with applied pressures. A range of polymer systems having varying flexibilities have been investigated for the insulating polymeric matrix. The use of carbon and  $\text{Fe}_3\text{O}_4$  particles have been investigated for use as the filler material. The amount of filler in the composites has been studied to determine the optimum solids loading. The different choices of filler and polymer have been investigated to determine which combination would yield the composites with the most pronounced changes in resistivity, as well as have increased reproducibility. Also, work has been done to minimize the volume of the sensor with respect to the volume of the entire smart package. The actuator for the proposed package consists of a commercially available PZT stack.

## LIST OF PUBLICATIONS

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## **REPORT OF INVENTION**

U.S. Patent Number 5,225,126: Piezoresistive Sensor; A.B. Alles and W.A. Schulze, Alfred University, Alfred, New York, July 6, 1993.

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